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Remote characterization of fire behavior during the FireFlux II experiment

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Abstract

The FireFlux II field experiment was conducted on January 30th, 2013 in south-east Texas, USA, under high fire danger conditions. The experiment was designed to study the behavior of a head fire progressing through a flat, tall grass prairie, and it was informed by the use of a coupled fire-atmosphere model. Vegetation properties and fuel moisture were measured shortly before the experiment. Near-surface atmospheric conditions were monitored during the experiment using an elaborate meteorological instrumentation array. Fire behavior was observed through a combination of remote and in-situ sensors. Clements et al. (2019) presented the analysis of the experiment micrometeorology and in-situ fire behavior observations acquired using a thermocouple array. In this paper, we extend the study of fire behavior during the FireFlux II experiment with the analysis of remote sensing observations. Two thermal infrared and two visible cameras were deployed during the experiment. One thermal and one visible camera were mounted on a helicopter, whereas the other two cameras were installed on a 40-m-height tower next to the burn unit. The tower infrared camera covered a reduced area of interest coincident with the thermocouple array and it allowed monitoring the fire spread as well as measuring the spatially-resolved evolution of brightness temperature. Imagery collected from the helicopter allowed extending fire behavior measurements to the complete burn unit. While airborne IR footage was saturated and did not allow estimation of emitted radiant heat, its analysis allowed tracking fire progression through the plot and therefore estimating rate of spread and fire time of arrival. The existence of in-situ temperature observations provides an outstanding opportunity to validate remote sensing methodologies. In addition, the combination of remote observations with in-situ fire and fuel measurements allows a comprehensive characterization of fire behavior, including spatially-resolved fire rate of spread and fire time of arrival, fire radiative power, Byram's fire line intensity, and air temperature during fire front passage. This paper presents preliminary results from this analysis. Such results demonstrate the usefulness of the selected datasets and the potential of the proposed methodology, encouraging further work. Possible applications of the resulting dataset include (i) the validation of existing fire behavior models that are able to predict any of the measured variables, (ii) the development of data-driven fire behavior models, and (iii) the investigation of the relative contribution of radiative and convective heat transfer mechanisms to fire spread.

1. The FireFlux II field experiment

This section summarizes the aspects of the FireFlux II experiment that are the most relevant for the present study. A complete description of the experiment design, instrumentation and measurements can be consulted in Clements et al. (2019). **Experimental site**

The FireFlux II experiment was conducted at the University of Huston Coastal Center (HCC) in Galveston County near La Marque, Texas, approximately 45 km south-east of Huston and 22 km north-west of Galveston Bay. The burn unit used in this experiment was a Texas Gulf Coast tall grass prairie, 40 ha in extension and situated 5 m above mean sea level (MSL). The last time it had been burned before FireFlux II was in 2006 during the first FireFlux experiment.

1.1. Experiment design

This fire experiment took place on 30 January 2013 under a regional burn ban and high fire danger conditions. The main goal of FireFlux II was to measure the behavior of a high-intensity head fire and monitor the corresponding near-surface atmospheric conditions. This was achieved by deploying a multifaceted set of instruments. Various platforms were used to deploy the sensors, including meteorological towers, surface fireproof sensors, and one helicopter. Figure 1 shows the experiment layout.

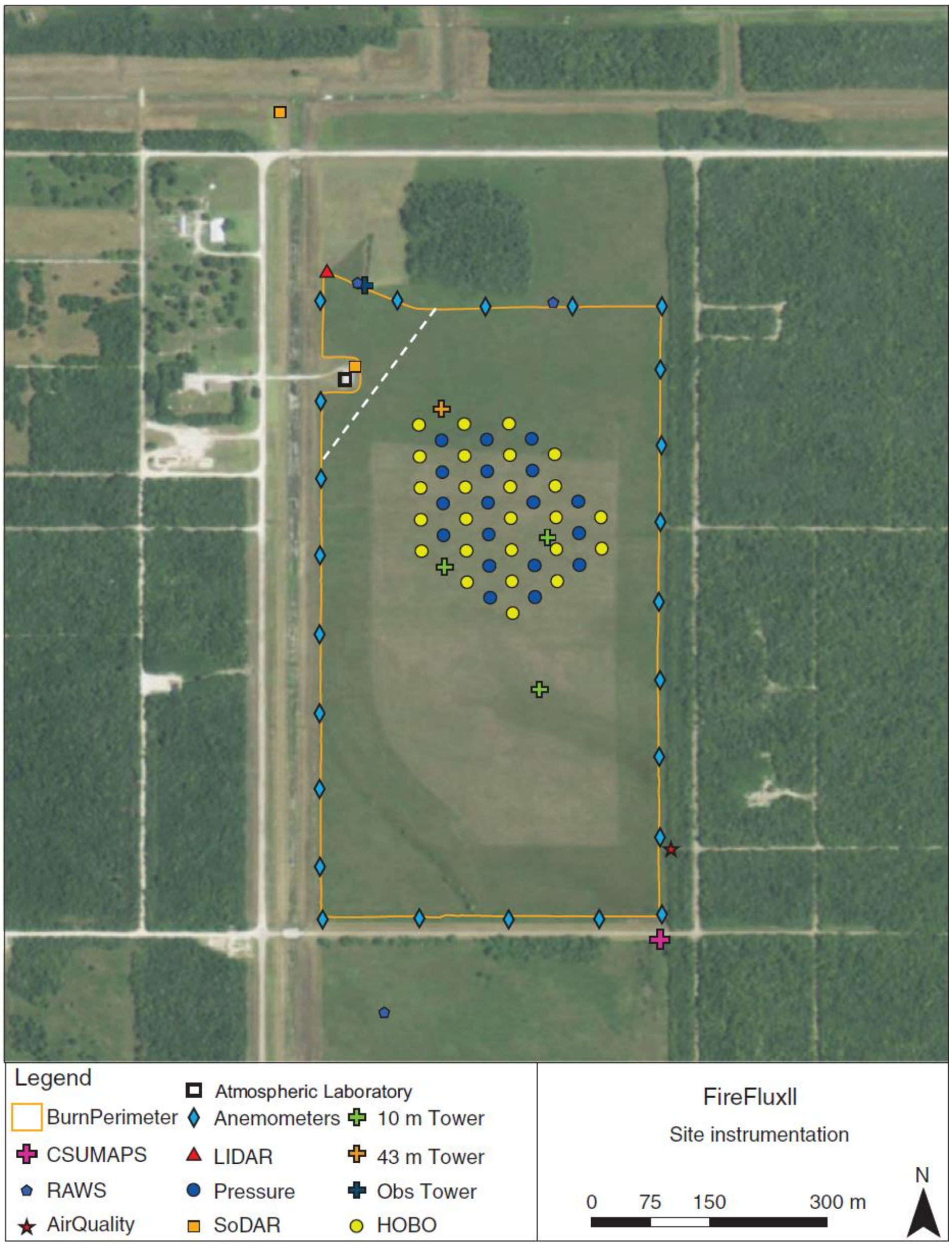

Figure 1- FireFlux II experiment layout (figure reproduced from (Clements et al. 2019)).

1.2. Atmospheric measurements

An array of towers distributed inside the burn unit constituted the primary source of meteorological data. A permanent 43-m meteorological tower is situated in the middle of the northern half of the burn unit. Additionally, three 10-m meteorological towers were installed south of the 43-m tower following a diamond pattern. Each tower was instrumented with arrays of 3D sonic anemometers, thermocouples, barometric pressure sensors, and radiometers. An additional meteorological tower was located outside the burn unit on the south-east corner and collected thermodynamic and wind profiles using 3D and 2D sonic anemometers, temperature and relative humidity probes.

Other instrumentation outside the burn unit included two Doppler sodars that provided 10-m average vertical wind profiles between 10 and 600 m above ground level (AGL), a Doppler lidar that captured radial velocities and backscatter intensities within the plume, three automated weather stations which measured wind speed and direction, air temperature and relative humidity, and an array of anemometers deployed along the burn unit perimeter to measure surface winds. Twenty-four cup-vane anemometers were installed at a height of 3.3 m AGL and spaced approximately 20 m apart from each other.

Finally, a radiosonde was launched before the ignition and recorded vertical atmospheric profiles of temperature, dew point temperature, and wind speed and direction.

1.3. Fuel sampling

Vegetation was sampled four weeks before the experiment to characterize the structure and loading of combustible material within the burn unit. Twenty destructive clip plots were established on a systematic grid within the burn unit at 25-m spacing. Fuel loading was determined from net dry vegetation weights measured after oven-drying vegetation samples at 70°C and surface-area-to-volume ratio was estimated by a detailed analysis of fuel particle geometry. Fuel loading was measured again after the experiment following a similar procedure in order to determine biomass consumption. Fuel moisture was sampled within 30 min of ignition.

2. Experimental Setup to Measure Fire Behavior

Fire behavior was monitored using a combination of in-situ and remote sensors. In-situ air temperature was measured by an array of thermocouples located at ground level and spaced 30 m apart (identified as *HOBOs* in Fig. 1). Remote instrumentation consisted of optical sensors working in the visible (VIS) and long-wave infrared (LWIR) spectral ranges. One VIS and one LWIR cameras were installed on a 40-m observation tower located at the north-west corner of the burn unit. Another VIS and another LWIR camera were installed on a helicopter that flew above the experimental site at about 450 m AGL. Figure 2 shows example frames from the different video sequences.

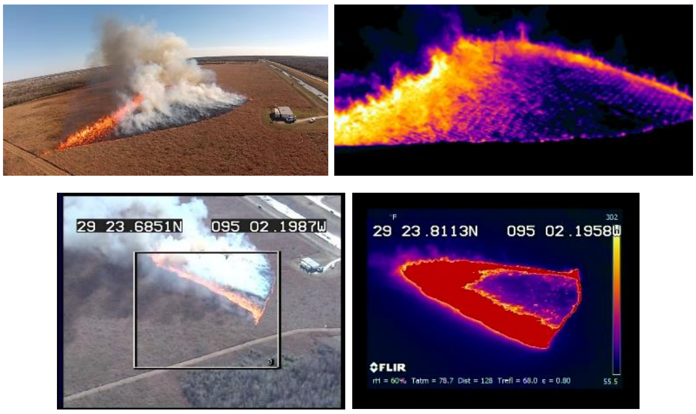

Figure 2- Example frames acquired by the four deployed cameras. Left: VIS, right: LWIR; top: tower-mounted; bottom: airborne.

3. Fire Behavior Characterization

Fire spread was monitored independently using three distinct data sources: the in-situ thermocouple array, the tower cameras, and the helicopter cameras. The observations from these three data sources overlap partially, which is leveraged in this study to accomplish a twofold objective. First, the overlapping regions are used to conduct a comparative analysis of different methodologies that are designed to yield the same result. Second, outcomes obtained from each methodology complement each other, and they are therefore combined to produce a unified dataset that contains comprehensive fire behavior metrics for the complete duration of the experiment.

3.1. In-Situ Thermocouples

Temperature profiles measured by in-situ thermocouples were used to identify the time of arrival of the fire to each sensor. Due to the lack of a unified criterion to identify fire arrival based on temperature time series, we explored three common approaches: identifying fire time of arrival as (a) the time at which the maximum temperature is reached, (b) the time at which the temperature gradient is the greatest, and (c) the time at which the temperature first exceeds a specified threshold. The three strategies produced similar results, although not identical (Fig. 3). Point estimations of fire time of arrival were interpolated to create a 2D map, as shown in Figure 4.

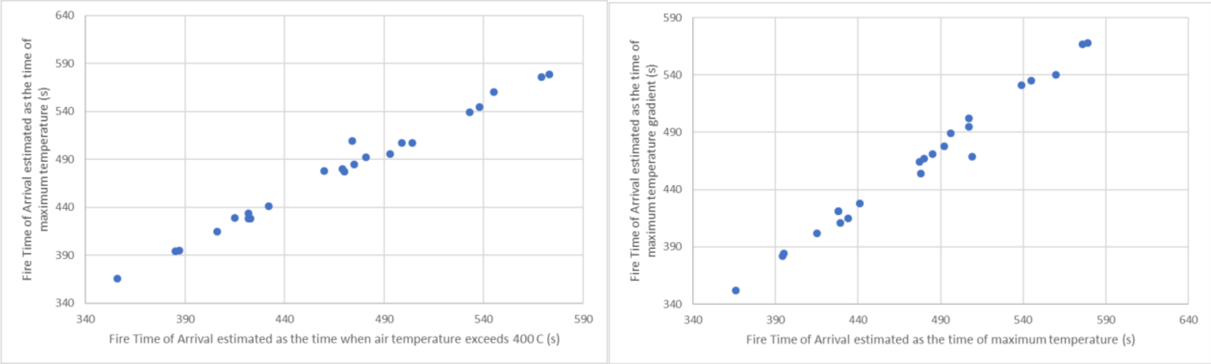

Figure 3- Comparison of different strategies to estimate fire time of arrival from in-situ air temperature measurements.

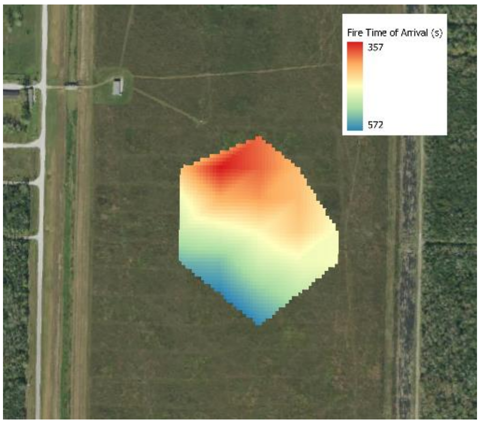

Figure 4- Fire time of arrival, relative to time of ignition, derived from in-situ air temperature measurements. Base image provided by the USDA National Agriculture Imagery Program.

3.2. Tower Remote Sensing

LWIR imagery acquired from the 40-m tower was still and provided a clear view of fire spread in a reduced area of interest, which allowed tracking the fire progression with high resolution and high positioning accuracy. The oblique imagery was geocorrected using ground control points. Resulting georeferenced brightness temperature fields were used to quantify fire progression and estimate fire time of arrival (Fig. 5). Fire progression was tracked using the methodology described in (Valero et al. 2018), whereas fire time of arrival was estimated as the time of maximum brightness temperature.

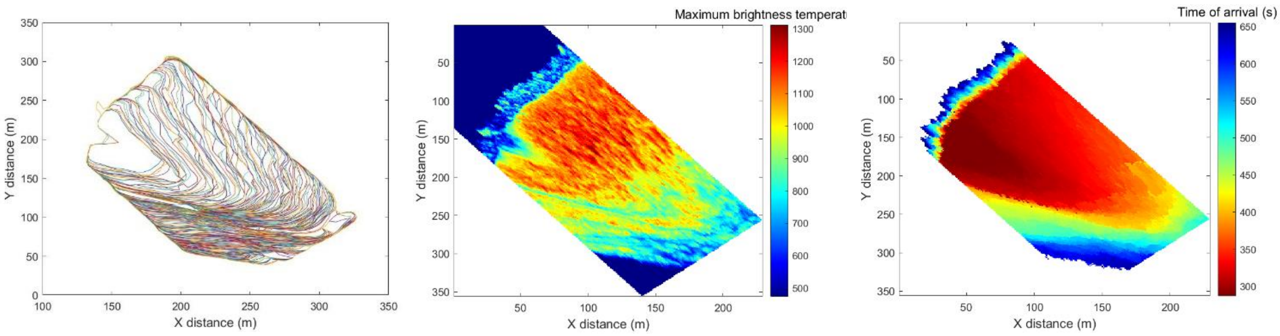

Figure 5- Fire progression (left), maximum brightness temperature registered at each location (center) and fire time of arrival relative to time of ignition (right) derived from the tower LWIR camera footage.

3.3. Airborne Remote Sensing

Airborne imagery complemented the information collected by in-situ and fixed remote sensors by covering a significantly larger area and tracking fire progression during the complete duration of the experiment. The LWIR airborne camera saturated and it therefore did not allow measuring the radiant heat emitted by the fire.

However, it was useful to track fire progression and estimate fire times of arrival for the complete burn unit (Fig. 6).

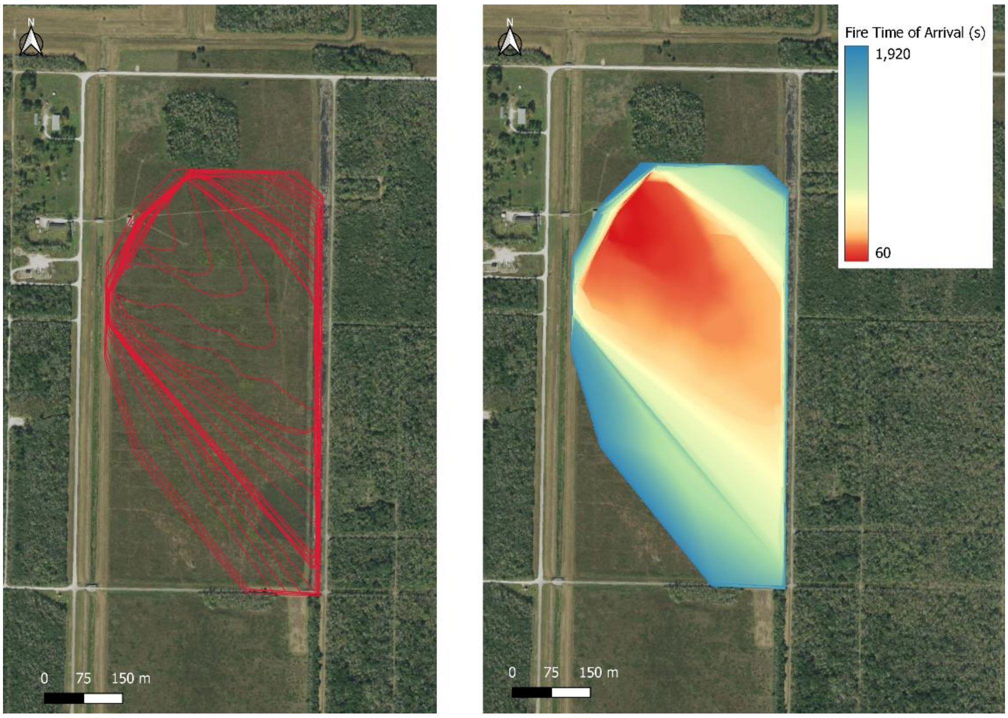

Figure 6- Fire progression derived from the airborne IR imagery. Left: fire perimeter at 60-s intervals. Right: fire time of arrival at every location in the burn unit, relative to the time of ignition. Base image provided by the USDA National Agriculture Imagery Program.

4. Conclusions and Future Work

In this paper, we present preliminary results of a detailed fire behavior analysis during the FireFlux II experiment. The results achieved so far demonstrate the utility of the three analyzed datasets and encourage further processing. Planned future work includes (i) conducting a detailed comparison of the measurements derived from each sensing technique, (ii) expanding the calculated results with additional fire behavior metrics, such as fire radiative power, rate of spread, and fire line intensity, and (iii) homogenizing the results and producing a comprehensive dataset that can be used in model validation exercises.

5. References

Clements, Craig B., Adam K. Kochanski, Daisuke Seto, Braniff Davis, Christopher Camacho, Neil P. Lareau, Jonathan Contezac, et al. 2019. "The FireFlux II Experiment : A Model-Guided Field Experiment to Improve Understanding of Fire – Atmosphere Interactions and Fire Spread." International Journal of Wildland Fire 28: 308–26. https://doi.org/10.1071/WF18089.

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